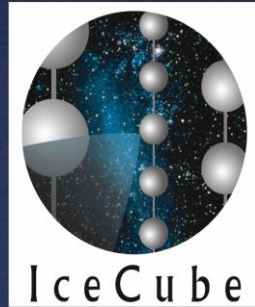# Sterile Neutrinos and IceCube

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whuelsn@fnal.gov

12 May 2011

Outline

- Introduction to IceCube

- Atmospheric neutrinos in IceCube

- Sterile neutrinos in IceCube

ScienceDaily (Dec. 19, 2010) — Culminating a decade of planning, innovation and testing, construction of the world's largest neutrino observatory, installed in the ice of the Antarctic plateau at the geographic South Pole, was successfully completed December 18, 2010, New Zealand time.
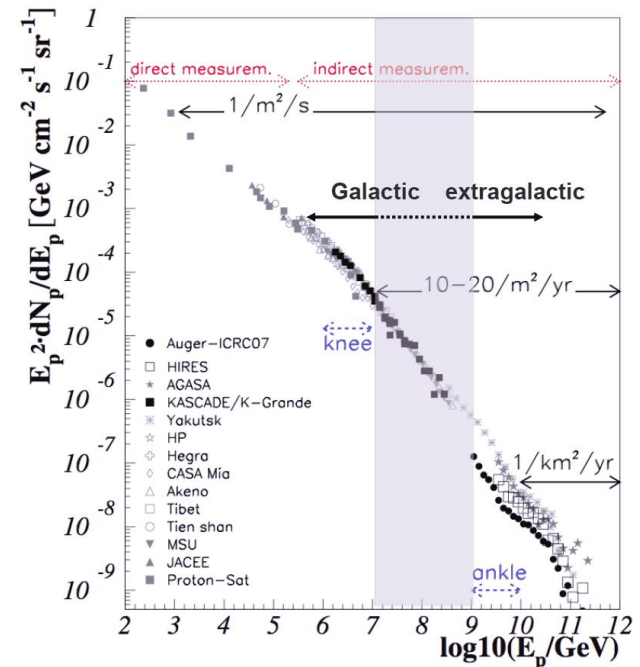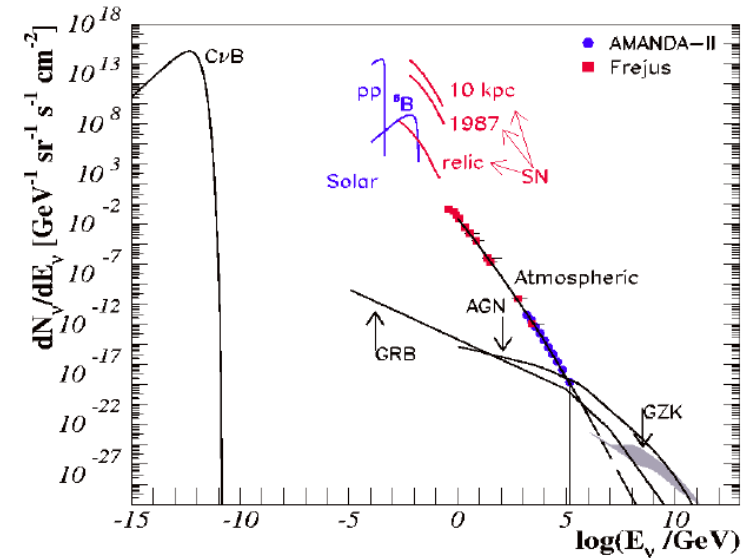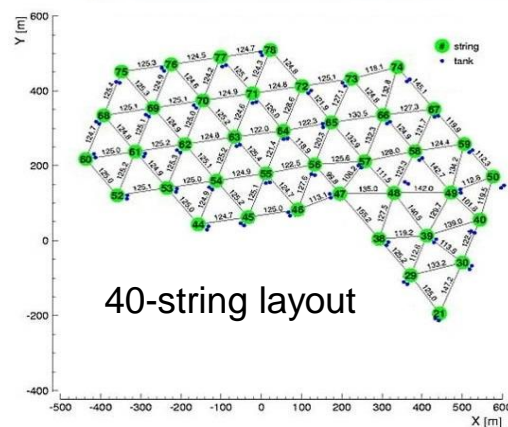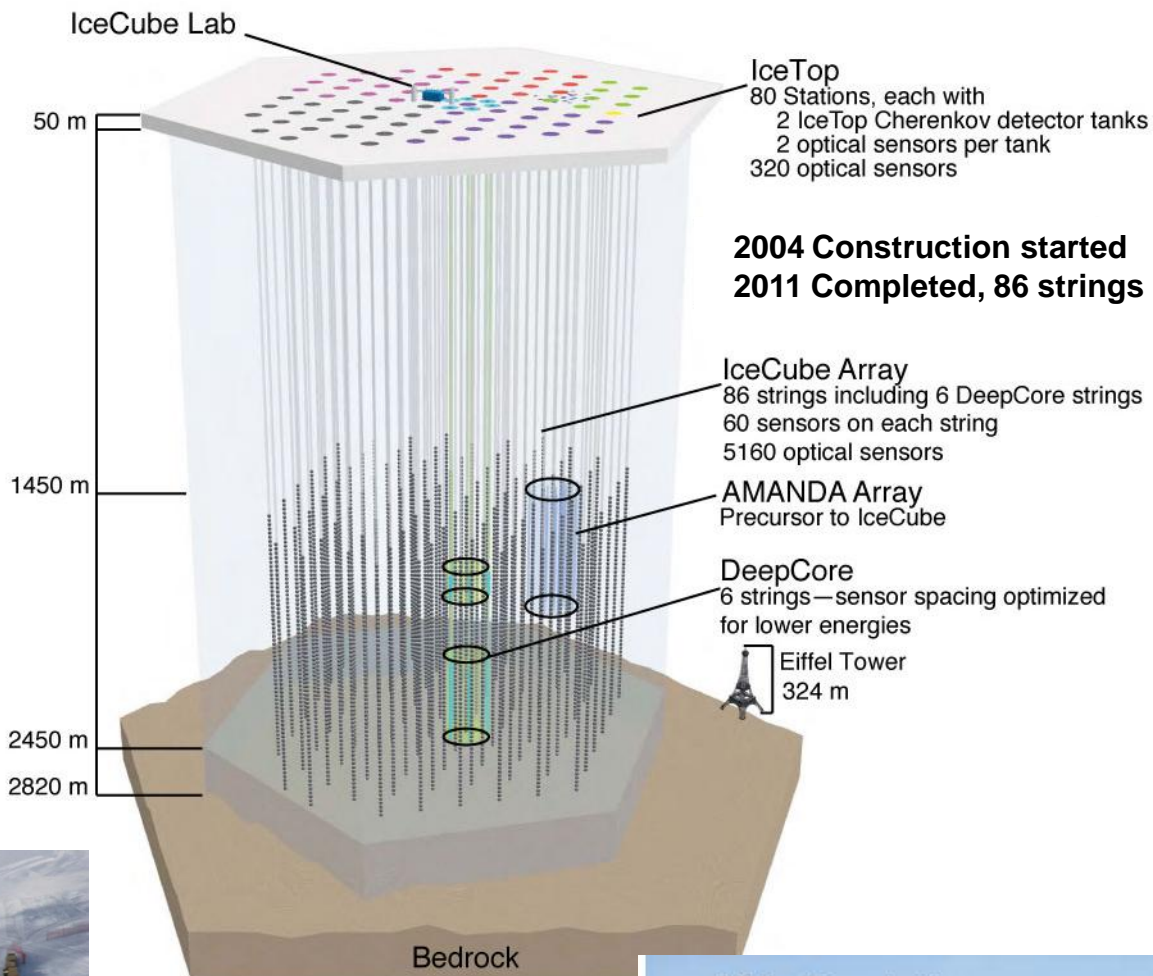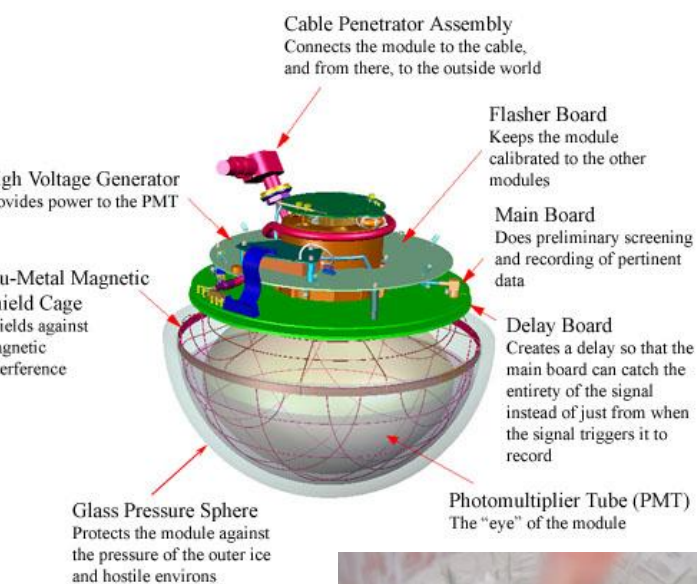
New window on the universe
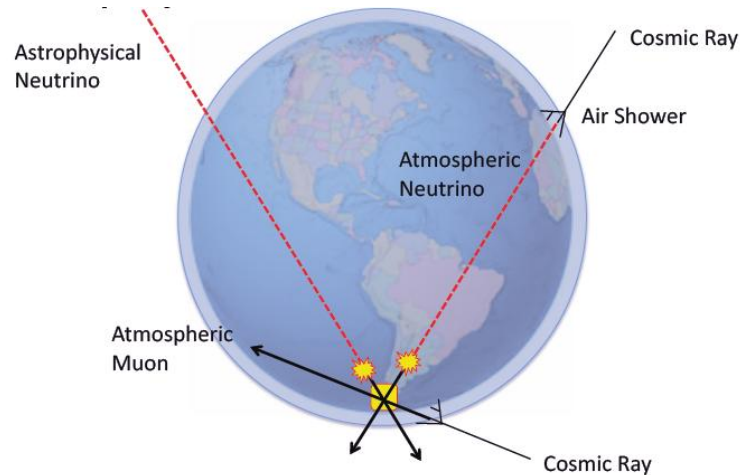
- **Why neutrinos?**
  - ➤ No strong or EM interactions
  - ➤ High Lorentz factors
  - ➤ Can provide new information about objects and processes in the universe
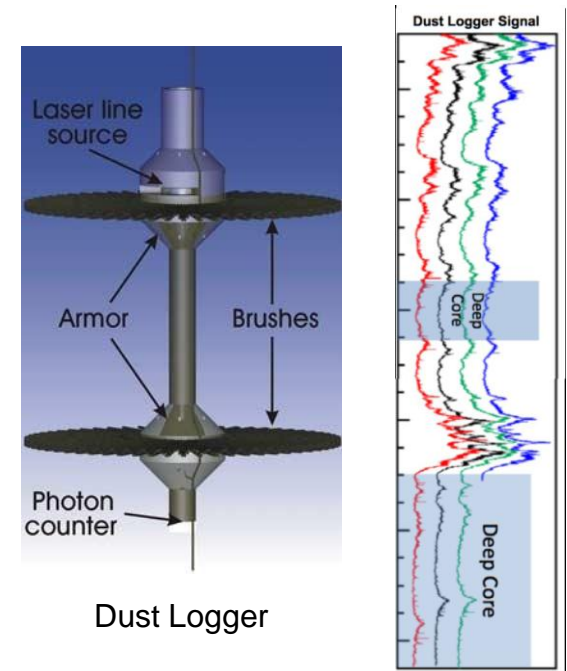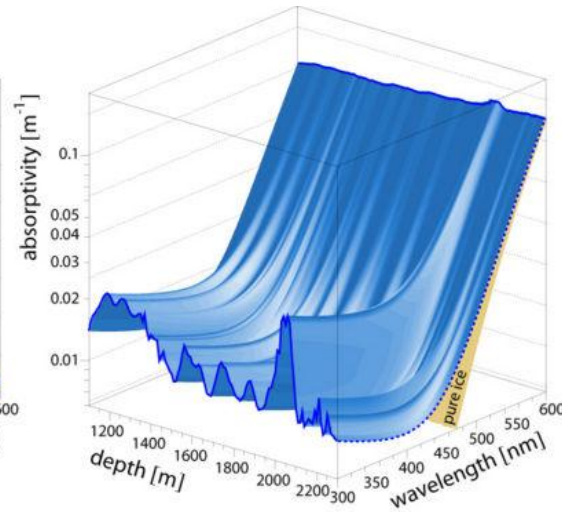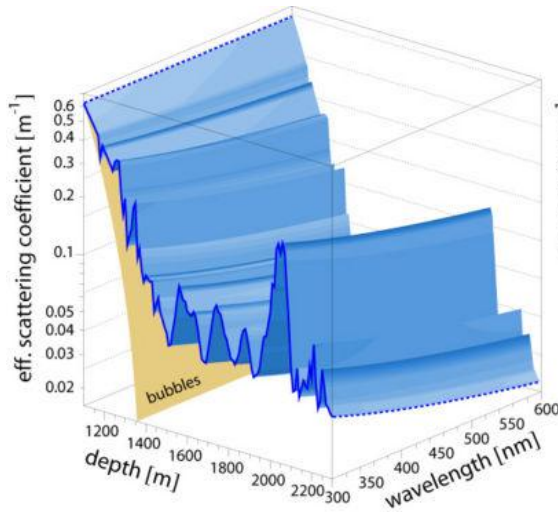 - ➤ Can probe new physics phenomena
- **Why the South Pole?**
  - ➤ Ice provides stable, transparent medium for propagation of Cherenkov photons
  - ➤ Provides overburden to reduce background of atmospheric muons
 - ➤ Large target volume for sufficient event rate for astrophysical neutrinos

Cable Penetrator Assembly
Connects the module to the cable, and from there, to the outside world

Flasher Board
Keeps the module calibrated to the other modules

Main Board
Does preliminary screening and recording of pertinent data

Delay Board
Creates a delay so that the main board can catch the entirety of the signal instead of just from when the signal triggers it to record

Photomultiplier Tube (PMT)
The "eye" of the module

gh Voltage Generator
ovides power to the PMT

u-Metal Magnetic
ield Cage
ields against
gnetic
erference

Glass Pressure Sphere
Protects the module against the pressure of the outer ice and hostile environs

IceCube Lab

50 m

1450 m

2450 m
2820 m

IceTop
80 Stations, each with
    2 IceTop Cherenkov detector tanks
    2 optical sensors per tank
320 optical sensors

**2004 Construction started
2011 Completed, 86 strings**

IceCube Array
86 strings including 6 DeepCore strings
60 sensors on each string
5160 optical sensors

AMANDA Array
Precursor to IceCube

DeepCore
6 strings—sensor spacing optimized for lower energies

Eiffel Tower
324 m

Bedrock

80 IceTop stations

40-string layout

Ice Properties

Dust Logger

Average optical parameters at 400 nm:

λ_{abs} ~110 m, λ_{sca} ~20 m above the dust layer

λ_{abs} ~220 m, λ_{sca} ~40 m below the dust layer

Effective scattering length vs Depth

Eff. Scattering length [m]

λ_e(400 nm) [m] vs. depth [m]
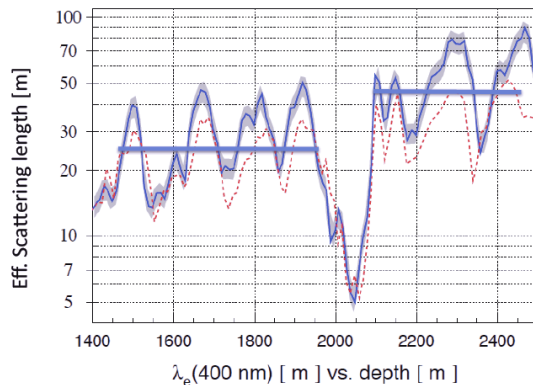
Absorption length vs Depth

Absorption length [m]

λ_a(400 nm) [m] vs. depth [m]
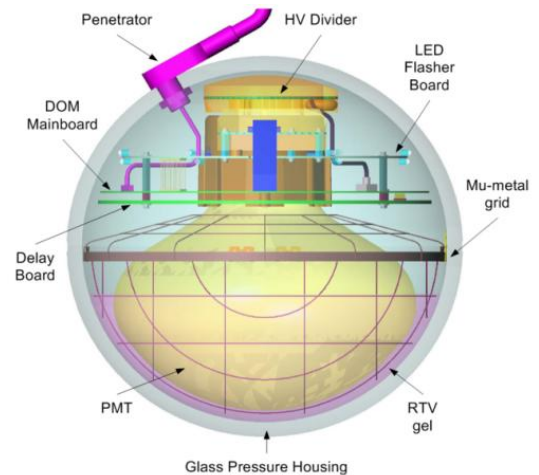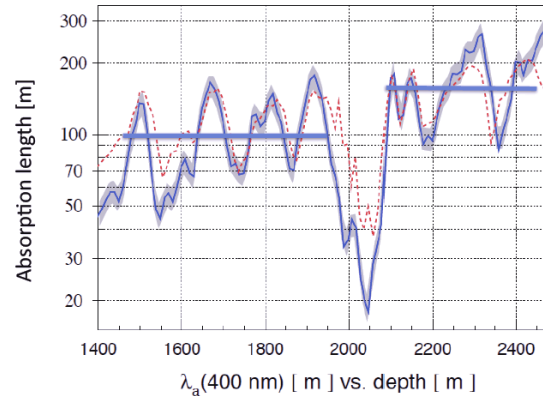
Digital Optical Module (DOM)
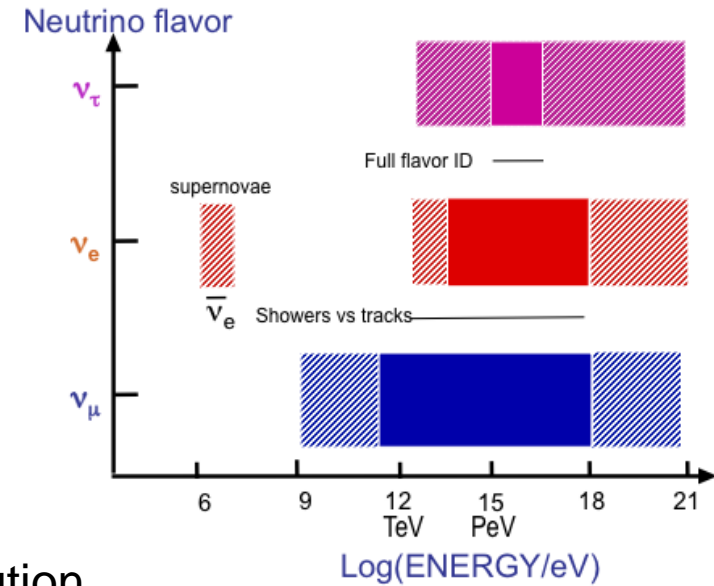
5

Neutrino Detection
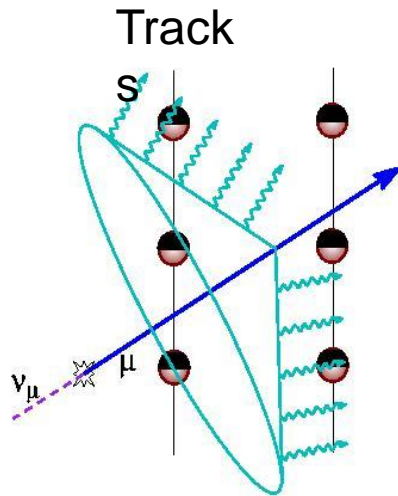
Track s

O(km) muon tracks
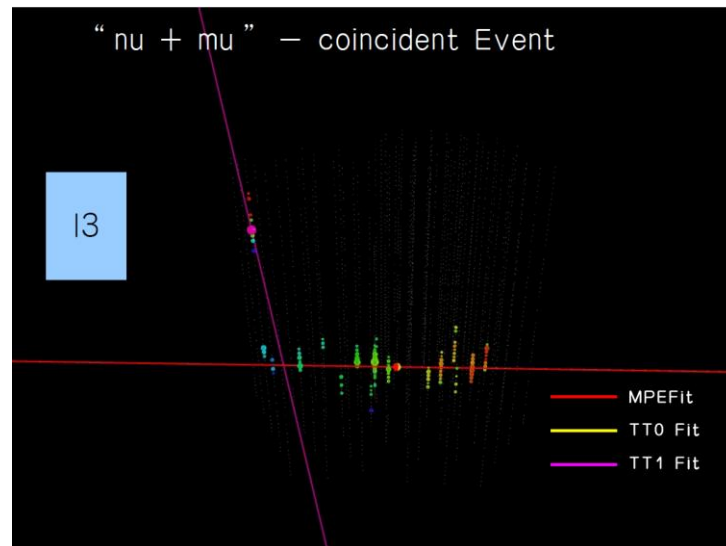
✓ Good angular resolution
✓ ν_μ CC events

Cascades
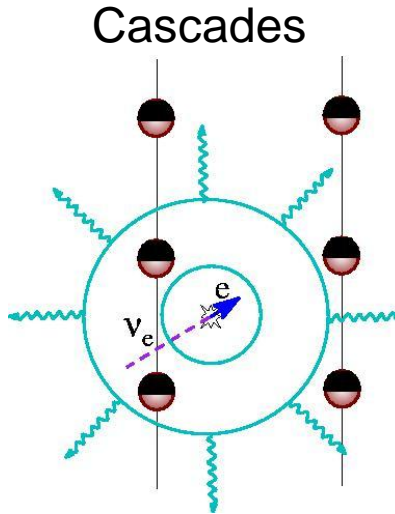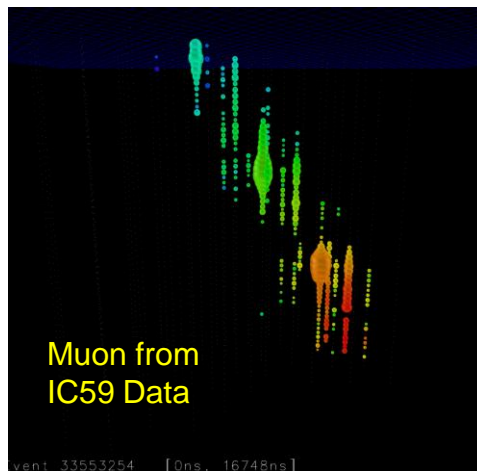
✓ Good energy resolution
✓ Little directionality
✓ 4π sensitivity
✓ All flavor sensitivity

Neutrino flavor

Full flavor ID ———

supernovae

$\overline{\nu}_e$ Showers vs tracks ———

Log(ENERGY/eV)
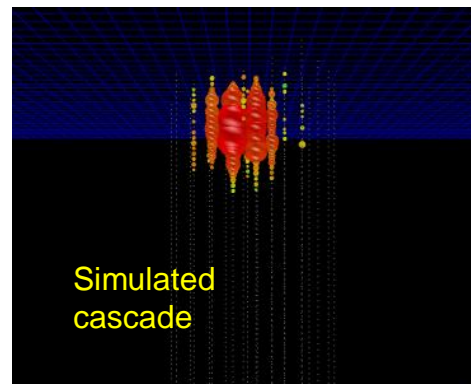
special case:

high energy ν_τ

Muon from
IC59 Data

vent 33553254   [0ns, 16748ns]

Simulated
cascade

Run 113203 Event 11202164
Fri Mar 20 06:07:16 2009

Zenith 1.23189
Azimuth 1.38119

Run 110860 Event 10601974 [0ns, 40000ns]

"nu + mu" — coincident Event

I3

MPEFit
TT0 Fit
TT1 Fit
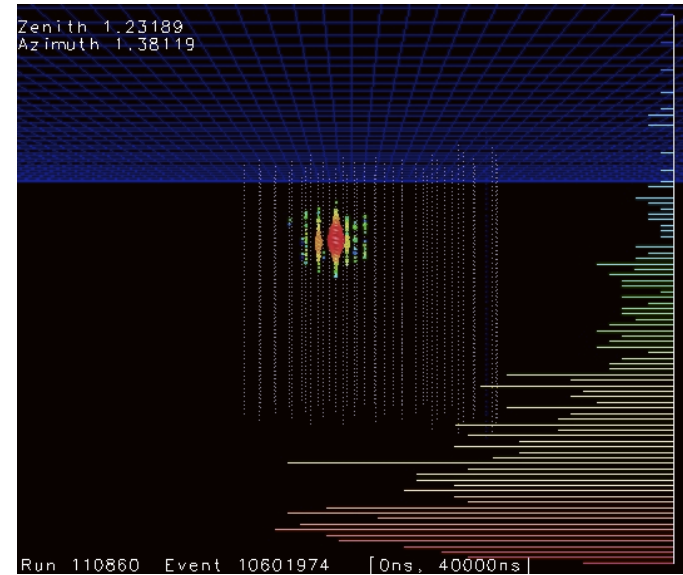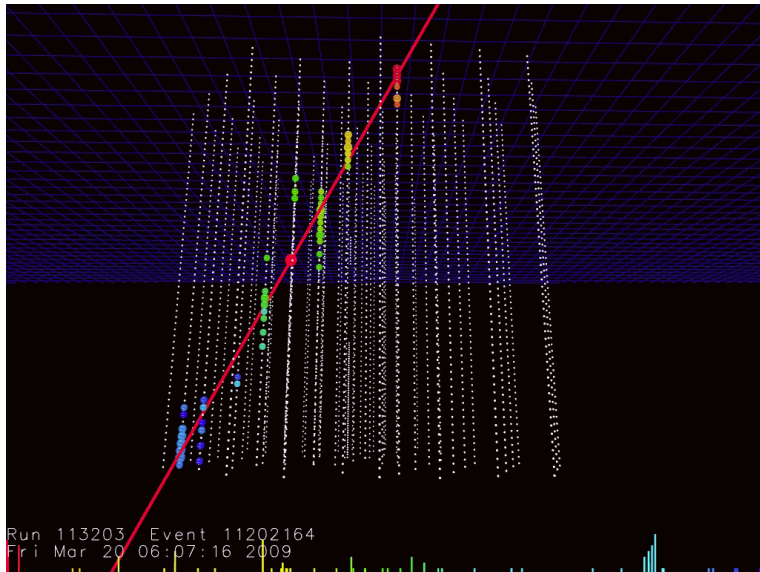
Astrophysical Point Source Search

IC40 All-Sky Point source search: Likelihood approach

Northern sky (ν bkg)

24h   0h

Southern sky (μ bkg)

$-\log_{10} p$

Hottest location in the all-sky search is:
   Ra=113.75°, Dec=15.15°
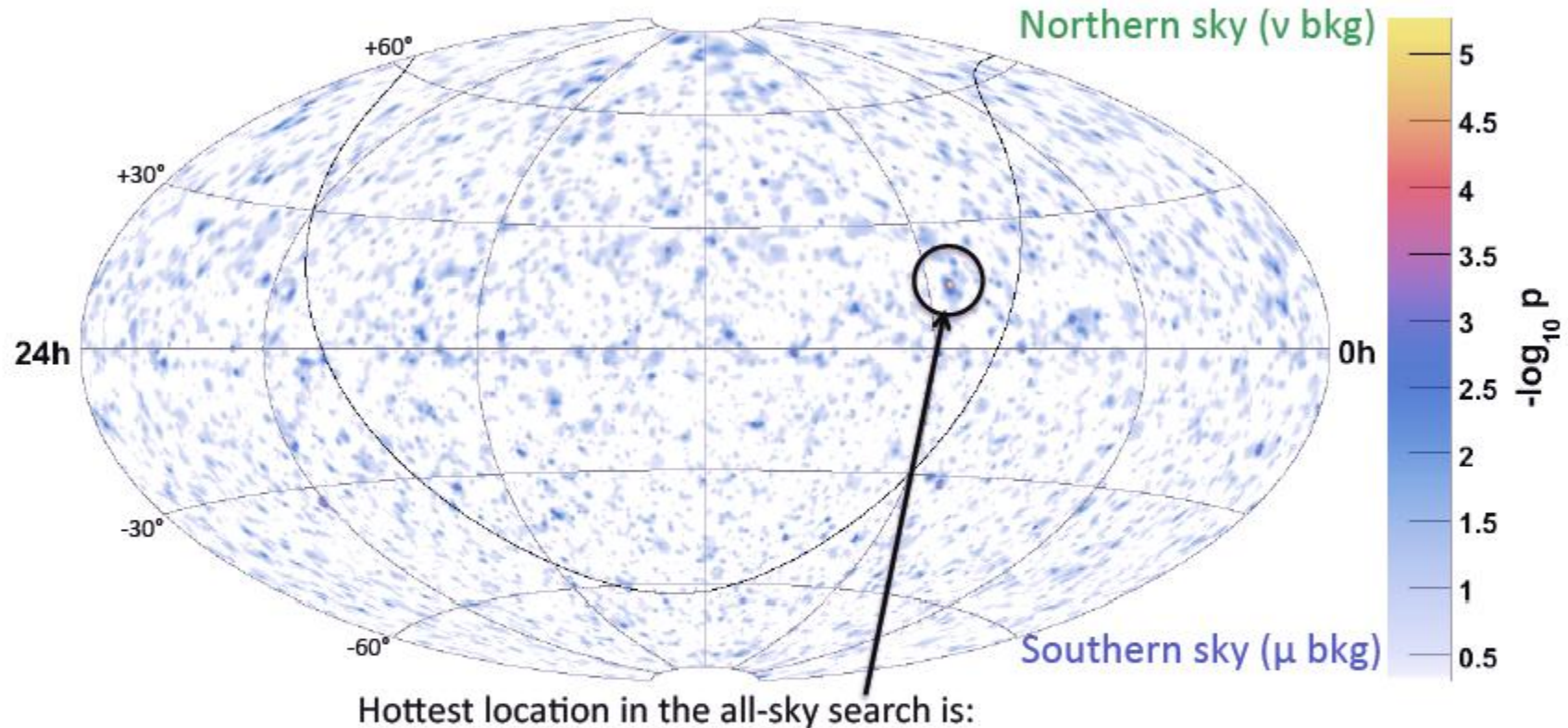
Livetime = 375.5 days

# Events = 36900
(14121 up-going,
22779 down-going)

In background simulated trials (scrambling data in r.a.), an
equal or greater excess occurs by chance 1817/10000 times.
=> **all-sky final p-value is 18%, not significant**

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arxiv:1012.2137, accepted by Astrophysical Journal

Atmospheric Muon Neutrino Flux

- SVD unfolding method described in A. Höcker and V. Kartvelishvili, NIM A 372 (1996) 469
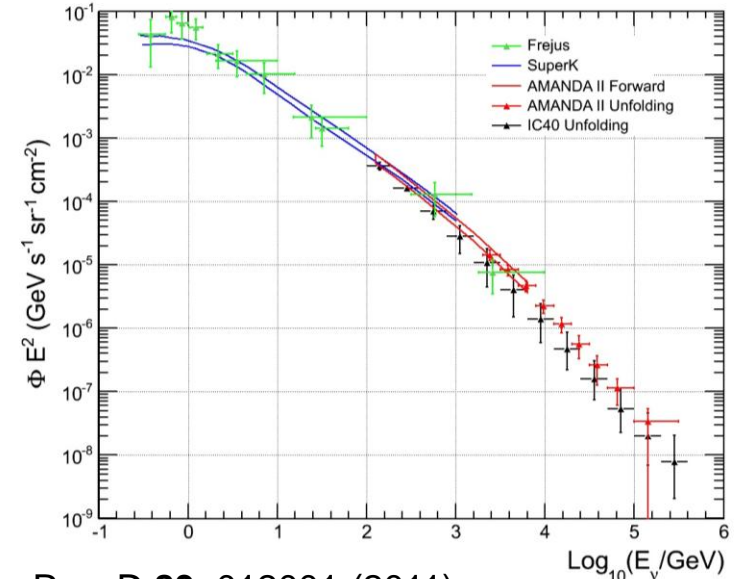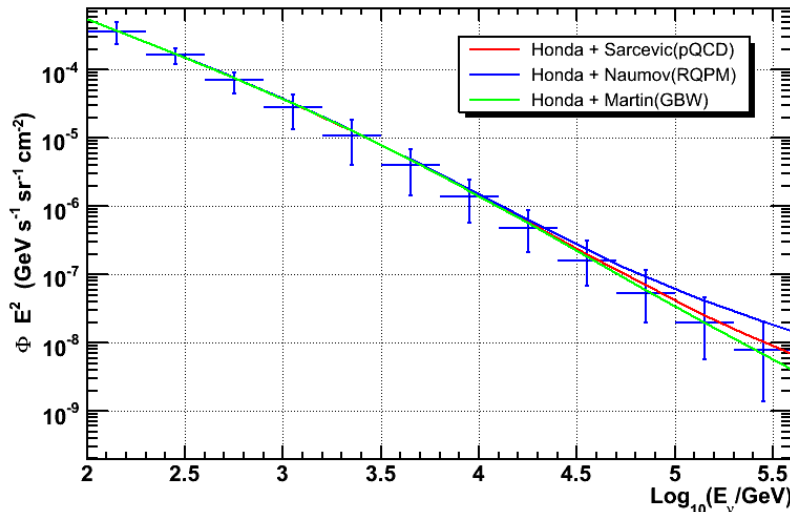- Implemented in RooUnfold: http://hepunx.rl.ac.uk/~adye/software/unfold/RooUnfold.html

Used only 97-180 zenith region in unfolding: 17689 events from IC40 data set
Observable was the reconstructed muon dE/dX

Observable used for the unfolding

Energy Coverage (from simulation) ~30% antiNeutrinos
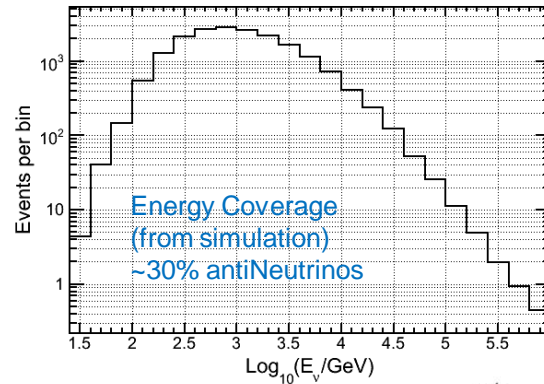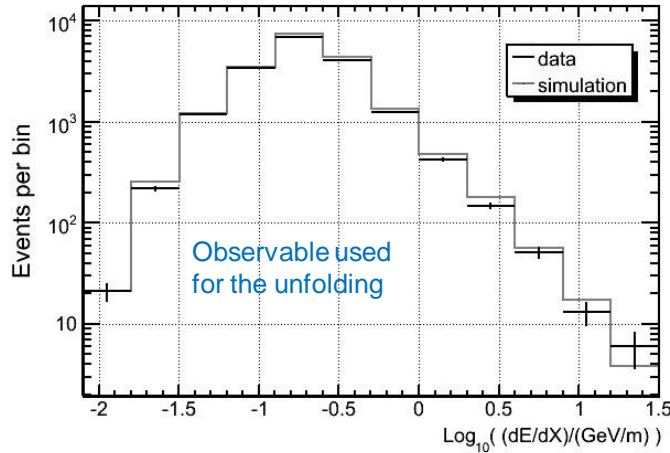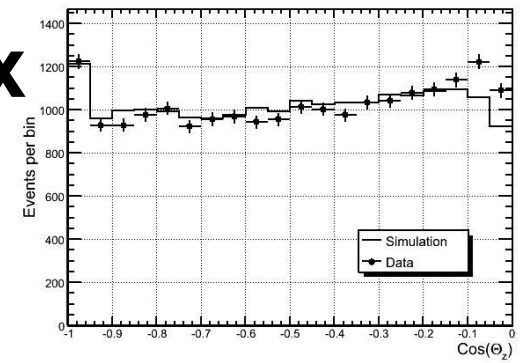
$$b(\frac{dE}{dX}) = A(E_\nu, \frac{dE}{dX})\Phi(E_\nu)$$

$$\Phi(E_\nu) = A^{-1}(E_\nu, \frac{dE}{dX})b(\frac{dE}{dX})$$
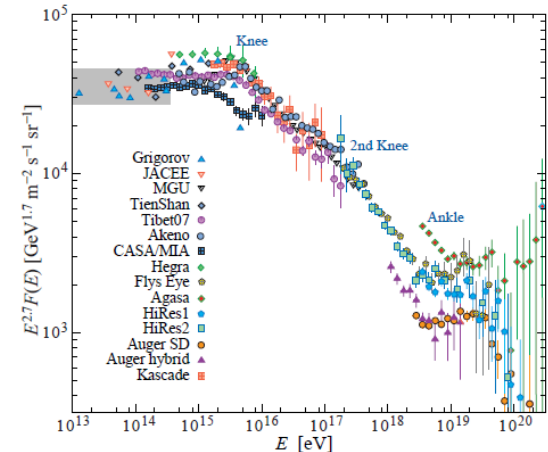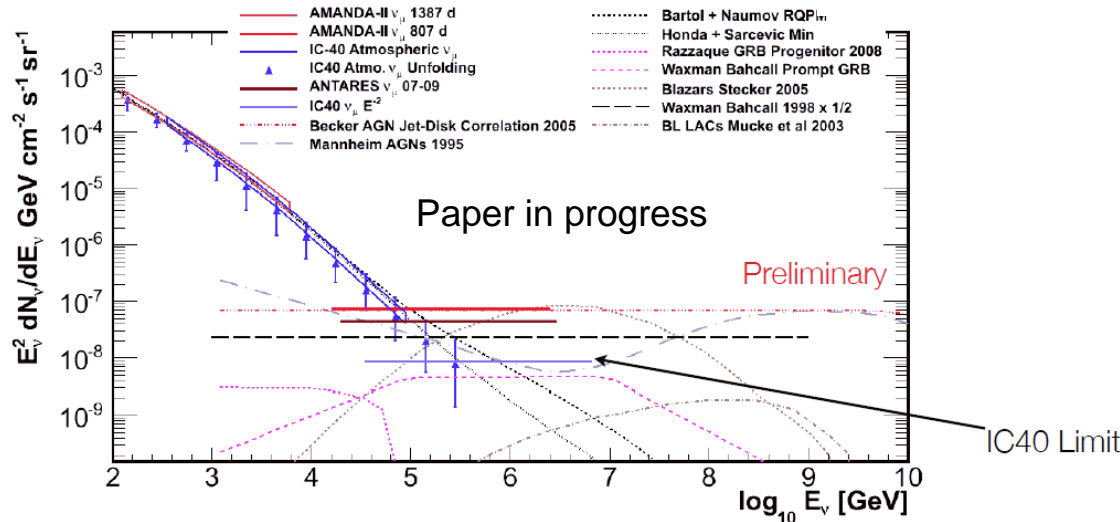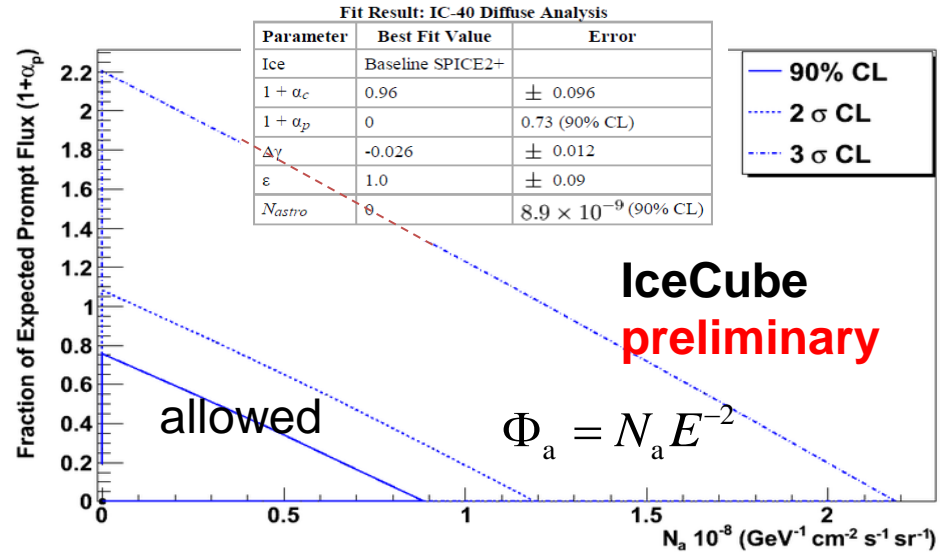

Phys. Rev. D **83**, 012001 (2011)

Prompt atmo and diffuse astrophysical

$$\Phi_p = \left(1 + \alpha_p\right)\left(\frac{E}{E_{median,p}}\right)^{\Delta\gamma} \Phi_{Enberg}$$
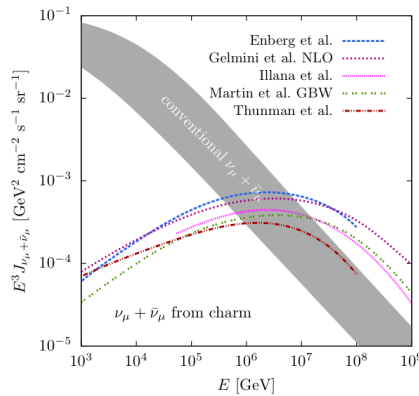
Result consistent with only K, π atmospheric ν to 100 TeV
Charm component not yet seen; "intrinsic" charm ruled out?

Fit Result: IC-40 Diffuse Analysis

Parameter	Best Fit Value	Error
Ice	Baseline SPICE2+	
$1 + \alpha_c$	0.96	$\pm$ 0.096
$1 + \alpha_p$	0	0.73 (90% CL)
$\Delta\gamma$	-0.026	$\pm$ 0.012
ε	1.0	$\pm$ 0.09
N_{astro}	0	8.9×10^{-9} (90% CL)

IceCube
preliminary

allowed

$$\Phi_a = N_a E^{-2}$$

Paper in progress

Preliminary

IC40 Limit

C. Amsler et al. (Particle Data Group),
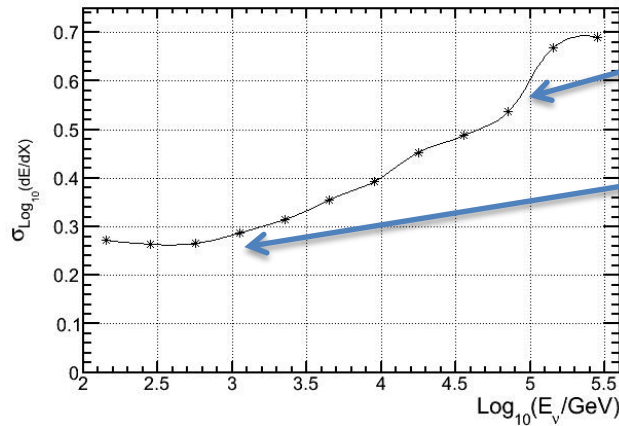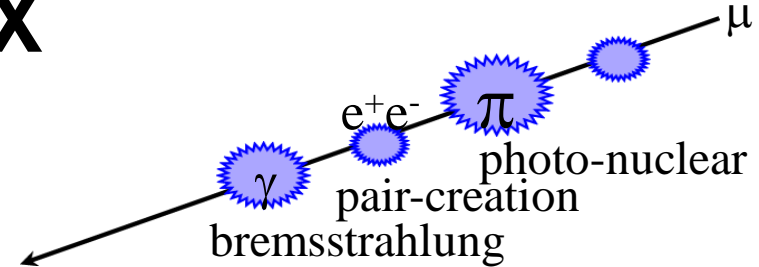Physics Letters B667, 1 (2008)

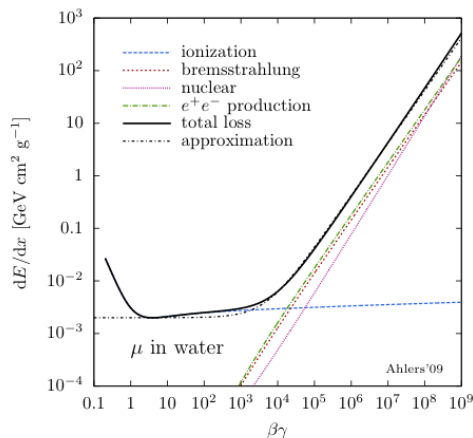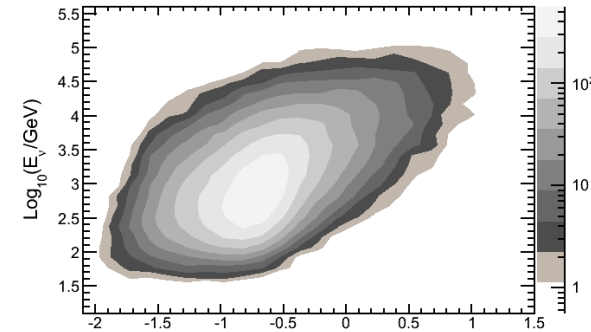limit on astrophysical $\nu_\mu + \bar{\nu}_\mu$, assuming E^{-2} spectrum
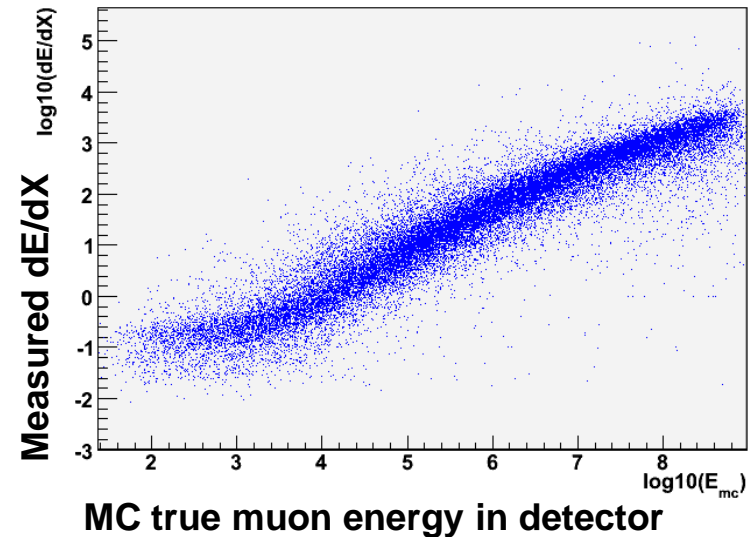
10

Energy Proxy: muon dE/dX

$$-\frac{dE_\mu}{dX} \approx \alpha(E_\mu) + \beta(E_\mu)\, E_\mu \Rightarrow \frac{\Delta E}{\text{IceCube}} \Rightarrow \frac{\sum \text{photons detected}}{\sum \text{photons predicted}}$$

μ

e^+e^- π

γ pair-creation photo-nuclear
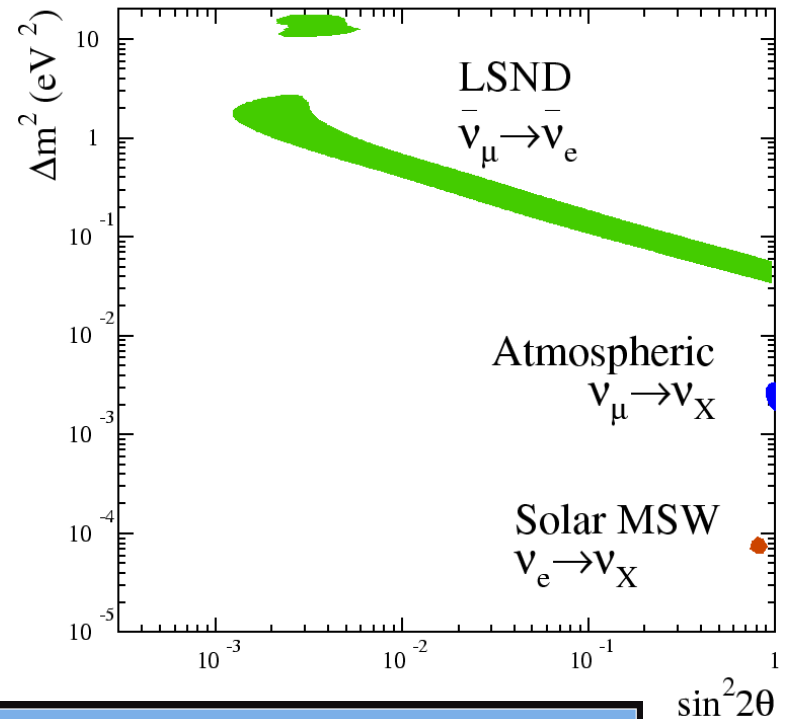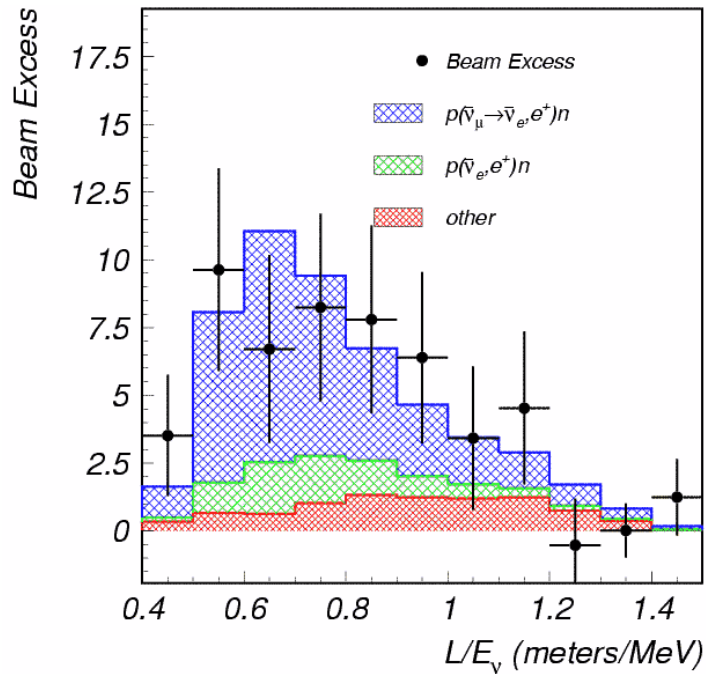
bremsstrahlung

- Muon energy loss outside detector hurts correlation with neutrino energy
- Energy dependence of muon track length in detector aids energy resolution
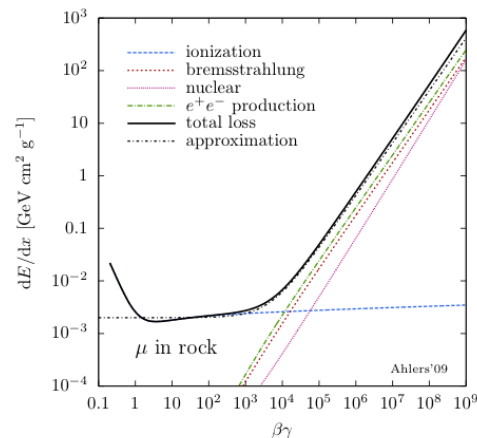
Energy Correlation

MC true muon energy in detector

LSND Saw an excess of $\overline{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

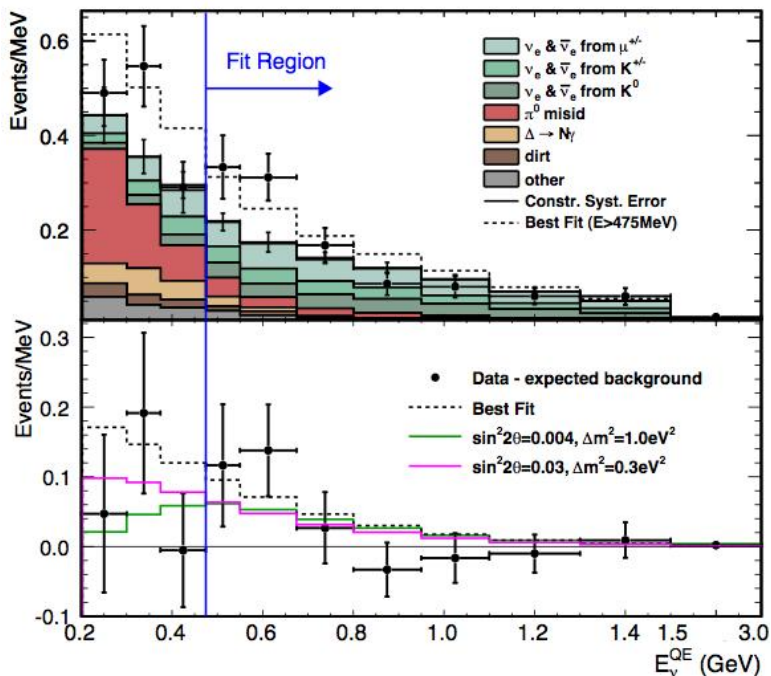**3.8 σ evidence for oscillation.**

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics!

Phys. Rev. D 64, 112007 (2001)

MiniBooNE Antineutrino Results (above 475 MeV)

anti-ν results

Above 475 MeV...

- In 475-1250 MeV, excess 20.9 ± 14 events (1.4σ)
- In 475-675 MeV, excess is 25.7 ± 7.2 events (3.6σ)
- True significance comes from fit over entire > 475 MeV energy region + numu constraint
- Best fit preferred over null at 99.4% CL (2.7σ)
- Probability of null hypothesis (no model dep.) is 0.5% in 475-1250 MeV signal region

Phys. Rev. Lett. **105**, 181801 (2010)

$\Delta\chi^2$ vs Δm^2
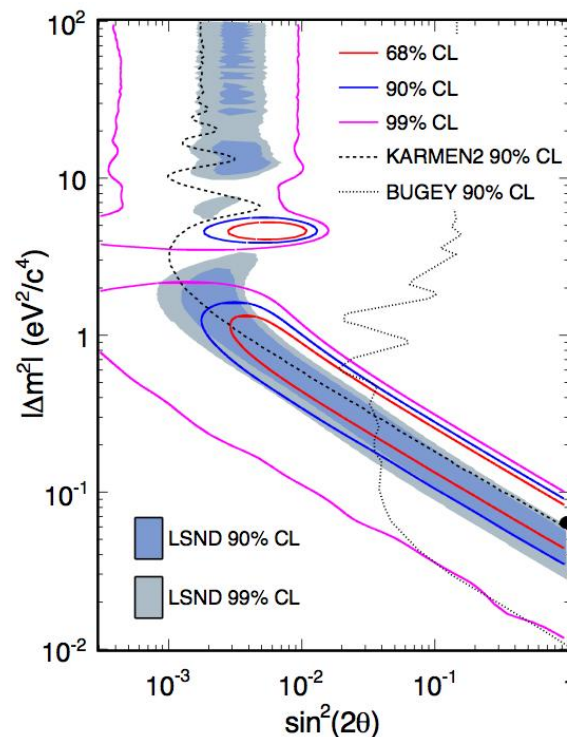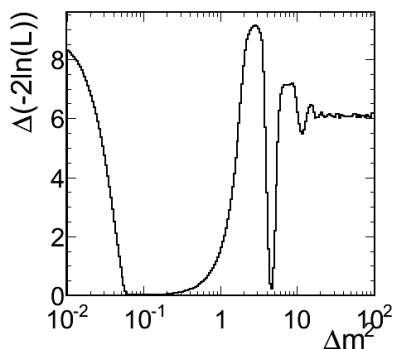
Sterile Neutrinos

Reactor Neutrino Anomaly

(G. Mention, et. al., arXiv:1101.2755)

"The no-oscillation hypothesis is disfavored at 99.86% CL"
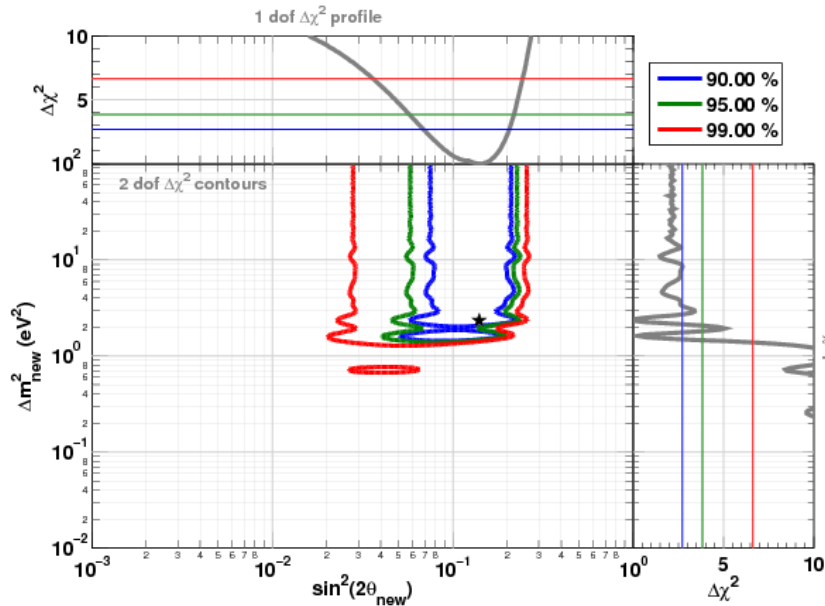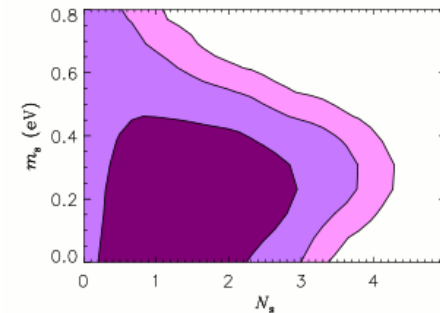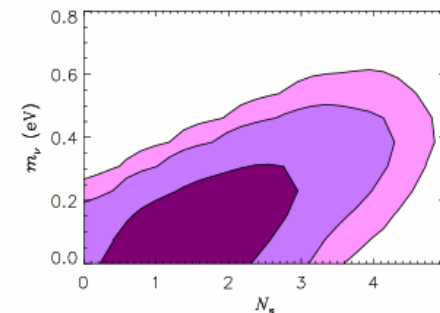

Cosmology Data Consistent with Extra, Sterile Neutrinos (J. Hamann, et. al. PRL 105 (2010) 181301)
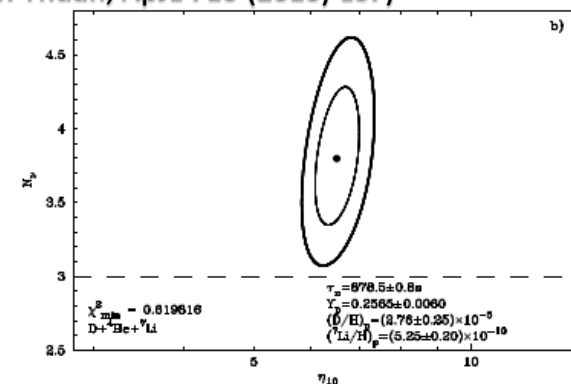

$3 + N_s$
$m_v = 0$

$3 + N_s$
$m_s = 0$

(Y. Izotov and T. Thuan, ApJL 710 (2010) L67)
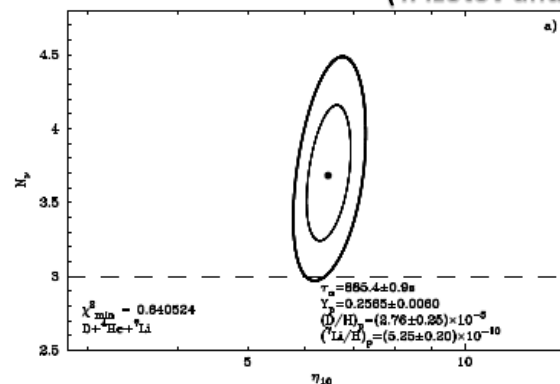
Mixing with sterile neutrinos?

3 active + n sterile neutrino states

$\Delta m^2_{43} \sim \Delta m^2_{LSND} \sim 1\ eV^2$

$\Delta m^2_{23} \sim \Delta m^2_{atm}$

$\Delta m^2_{12} \sim \Delta m^2_{solar}$

(not to scale)

m^2

$\sim |U_{\alpha i}|^2$

ν_e ν_μ ν_τ ν_s
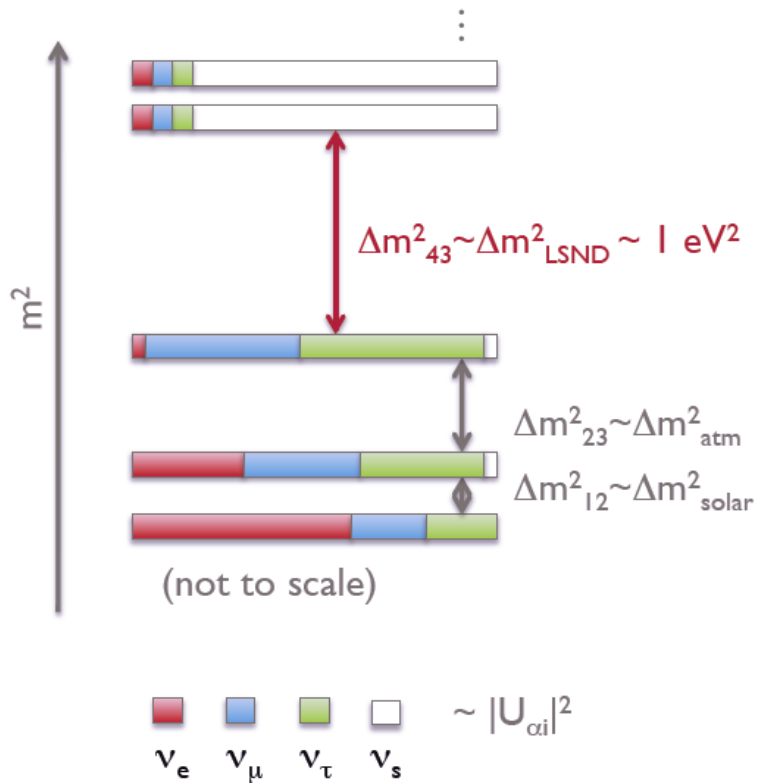
Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j\ |U_{\alpha i}\ U^*_{\beta i}\ U^*_{\alpha j}\ U_{\beta j}|\ sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

N	#Δm_{ij}^2	#θ_{ij}	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

Antineutrino Oscillations in 3+1 Schemes

Giunti and Laveder fits to global antineutrino data

$\bar{\nu}_\mu$ disappearance

IceCube and eV² scale mixing is like SuperK and 10^{-3} eV² scale mixing!!
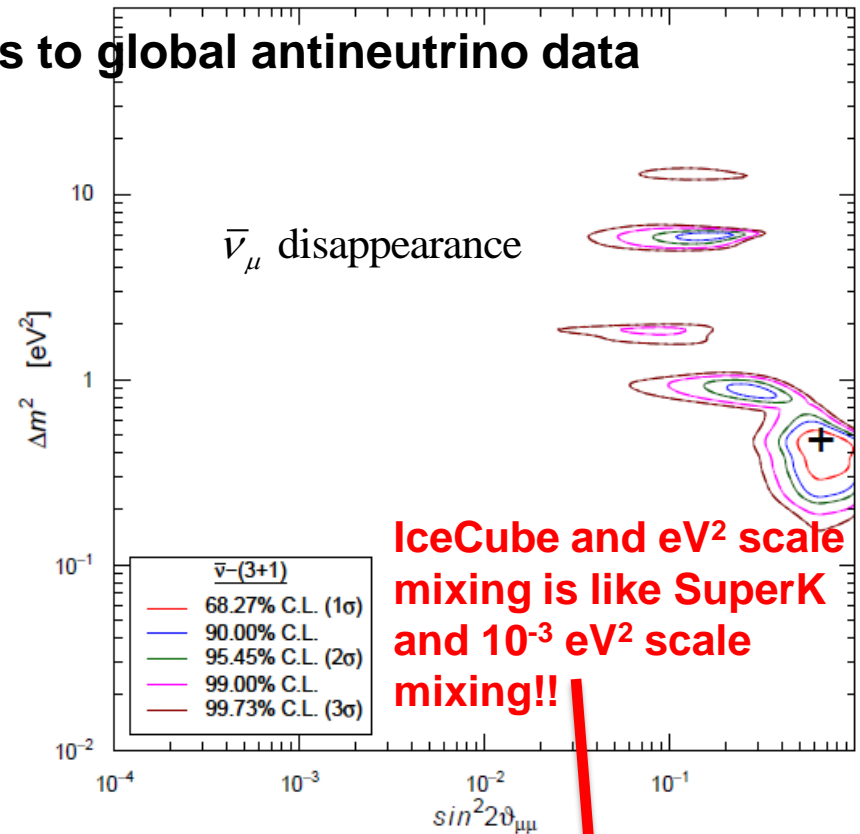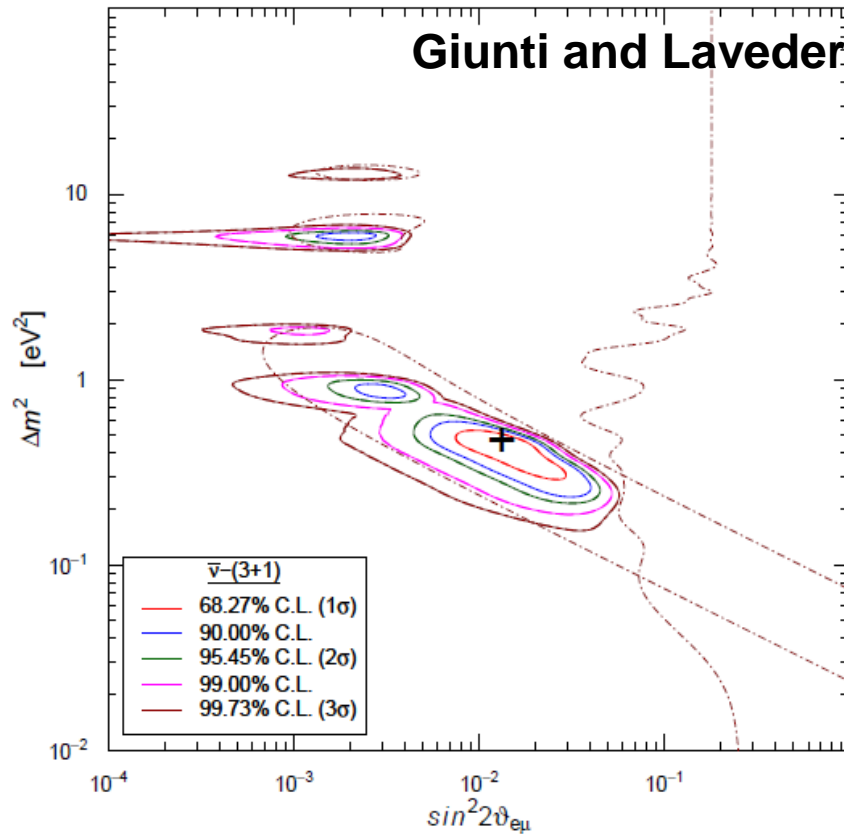
$$\chi^2_{min} = 82.0 \qquad NdF = 83 \qquad GoF = 51\%$$

$$\Delta m^2 = 0.45\,eV^2 \qquad \sin^2 2\vartheta_{e\mu} = 0.013 \qquad \sin^2 2\vartheta_{ee} = 0.017 \qquad \sin^2 2\vartheta_{\mu\mu} = 0.65$$

Prediction: large SBL $\bar{\nu}_\mu$ disappearance at $0.1 \lesssim \Delta m^2 \lesssim 1\,eV^2$

[Giunti, Laveder, arXiv:1012.0267]

C. Giunti — Recent Progress in Neutrino Physics — 1 Mar 2011 — 15/25

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Matter Effects for ~1eV² scale oscillations

S. Choubey, arXiv:0709.1937

$$\Delta m_M^2 = \sqrt{\left(\Delta m_{vac}^2 \cos 2\theta_{vac} - A_M\right)^2 + \left(\Delta m_{vac}^2 \sin 2\theta_{vac}\right)^2}$$

$$\sin 2\theta_M = \frac{\Delta m_{vac}^2 \sin 2\theta_{vac}}{\Delta m_M^2}$$
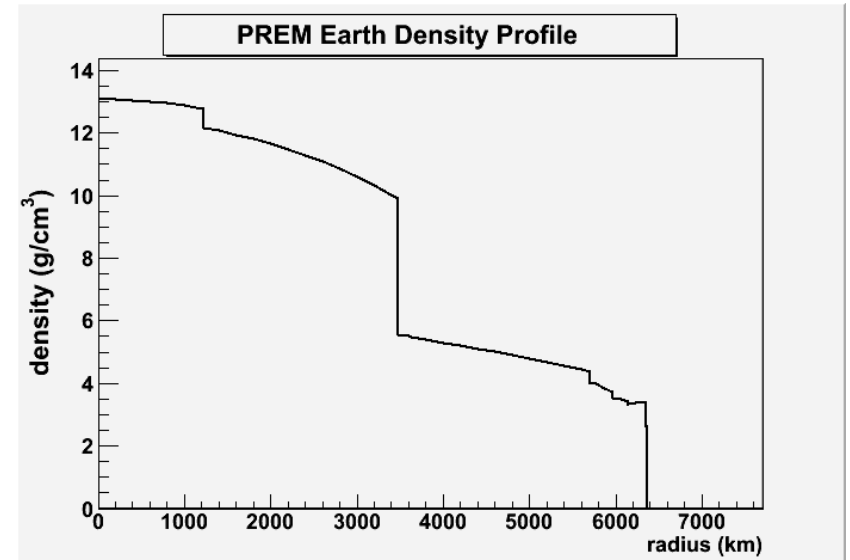
$$\cos 2\theta_M = \frac{\Delta m_{vac}^2 \cos 2\theta_{vac} - A_M}{\Delta m_M^2}$$

Due to ~1eV² mass scale, density of Earth, and the fact that the mixing is with sterile neutrinos, can't ignore "MSW" effect. Effective mixing parameters are now functions of energy and zenith angle

$$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_s : \quad A_M = A_{NC} = \sqrt{2} E_\nu G_F N_n$$

$$\text{for } \nu_\mu \leftrightarrow \nu_s : \quad A_M = -A_{NC}$$

$$N_n \approx N_e \approx 0.5 N_A \rho$$

PREM Earth Density Profile

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Matter Effects for ~1eV² scale oscillations

$$1 - \sin^2(2\theta_M)\sin^2\left(1.27\frac{\Delta m_M^2 (eV^2) L(km)}{E(GeV)}\right)$$

$$i\frac{d}{dx}\Psi = \frac{1}{2E}\left(UM^2U^\dagger + A\right)\Psi$$

$$i\frac{d}{dx}\begin{pmatrix} \psi_{\mu\mu} \\ \psi_{\mu s} \end{pmatrix} = \frac{\Delta m_M^2}{4E_\nu}\begin{pmatrix} -\cos 2\theta_M & \sin 2\theta_M \\ \sin 2\theta_M & \cos 2\theta_M \end{pmatrix}\begin{pmatrix} \psi_{\mu\mu} \\ \psi_{\mu s} \end{pmatrix}$$

$$P_{\bar{\nu}_\mu \to \bar{\nu}_\mu} = \left|\psi_{\mu\mu}\right|^2$$

Can generalize to include more than one active and/or more than one sterile neutrino

C. Giunti and C.W. Kim, *Fundamentals of Neutrino Physics and Astrophysics,* Oxford University Press, (2007)
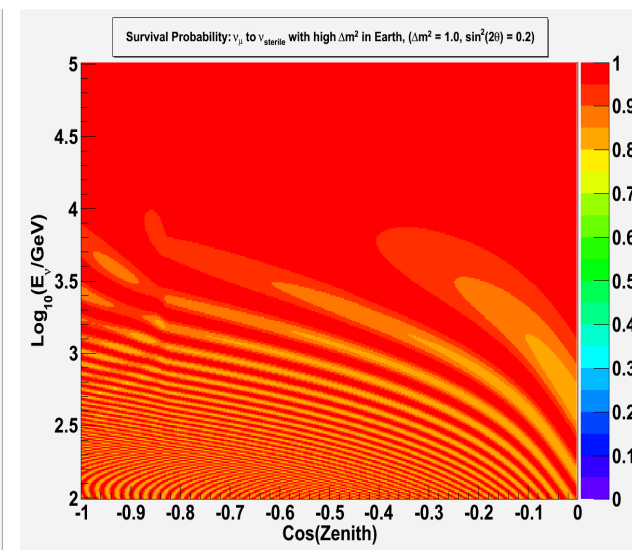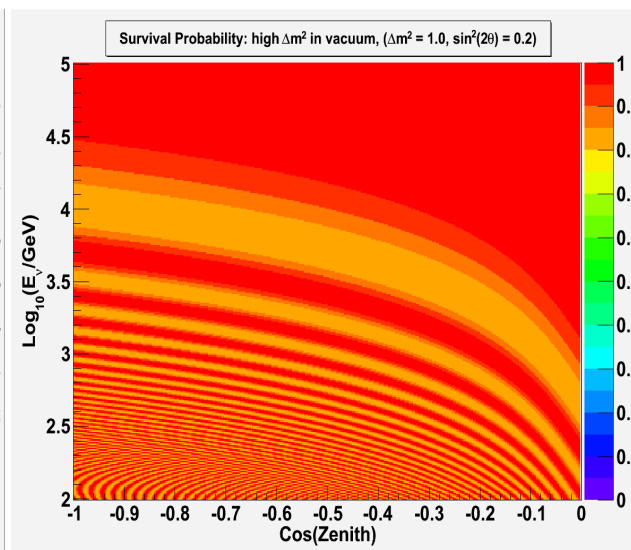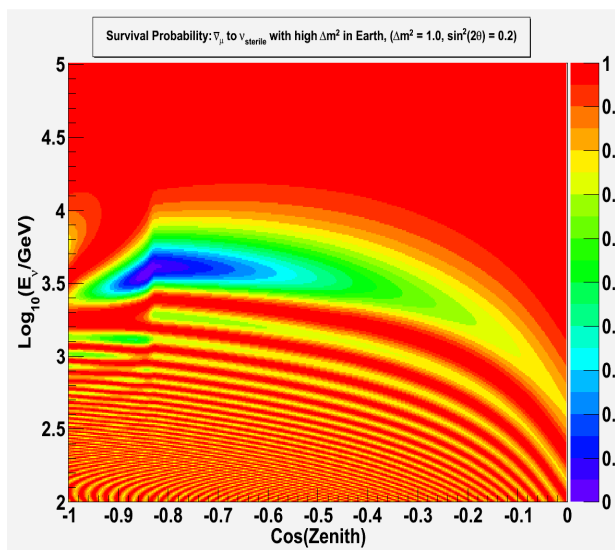
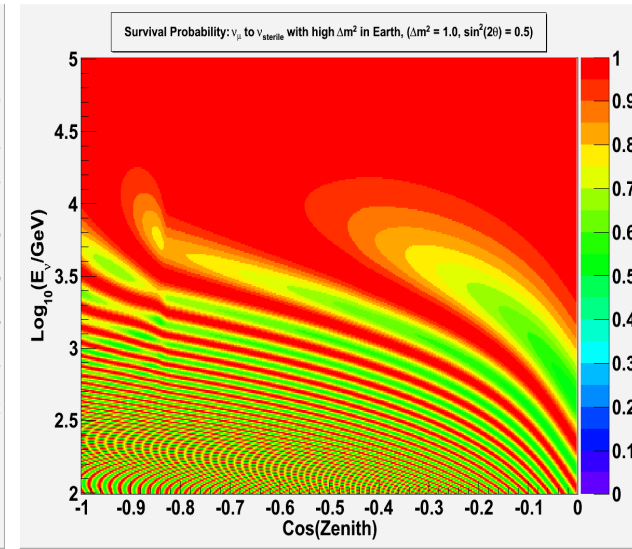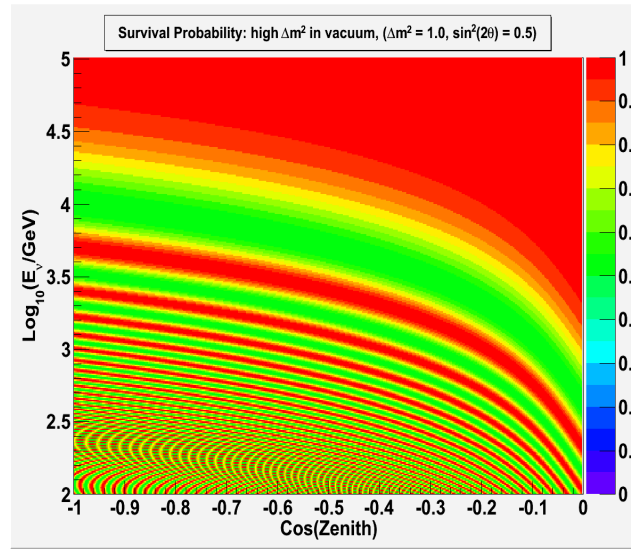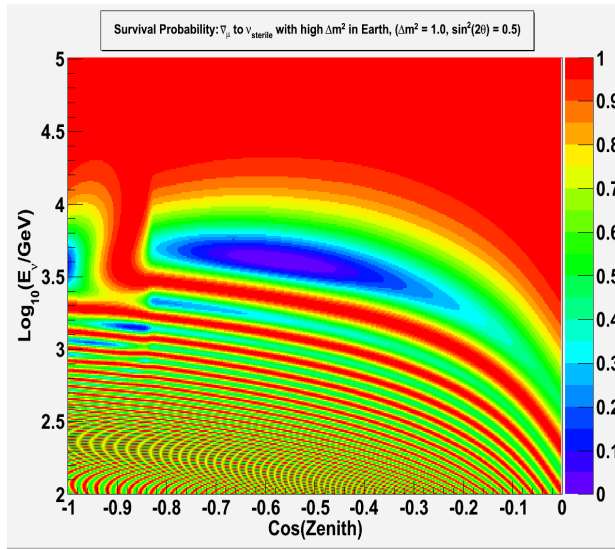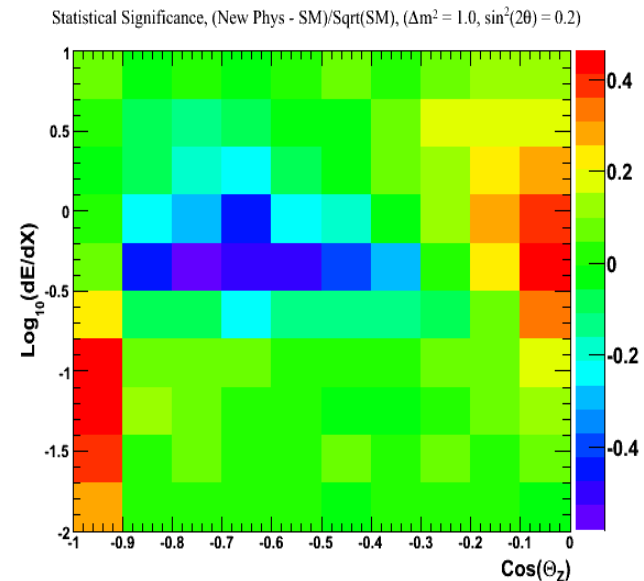# **Matter Effects in IceCube**

Oscillation survival probability as function of neutrino energy and zenith

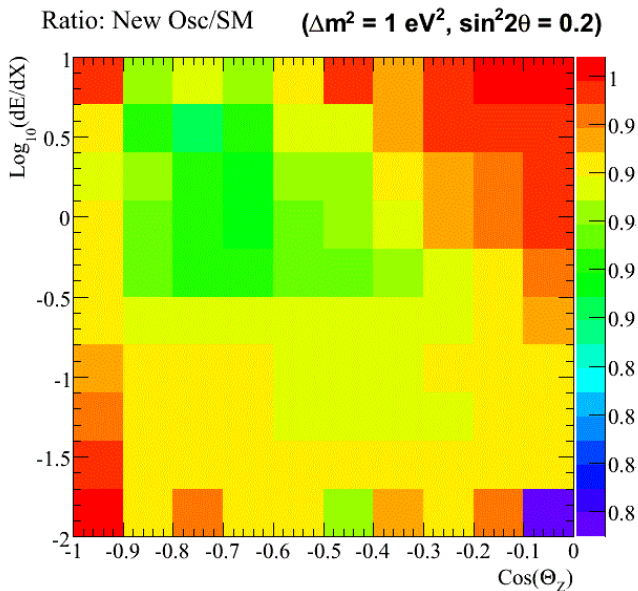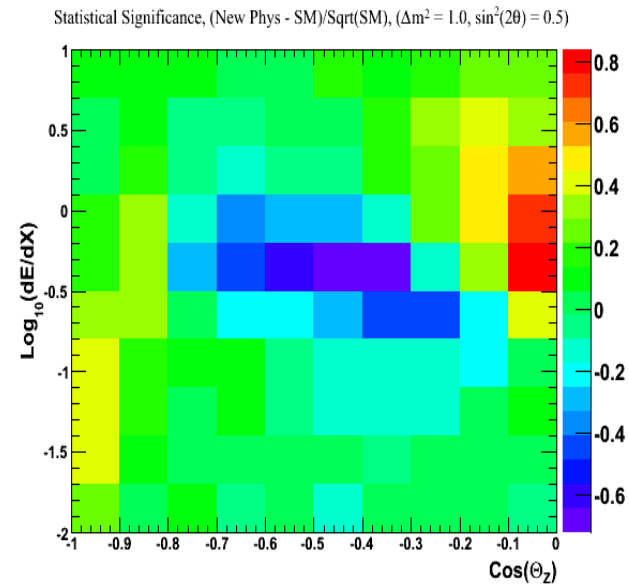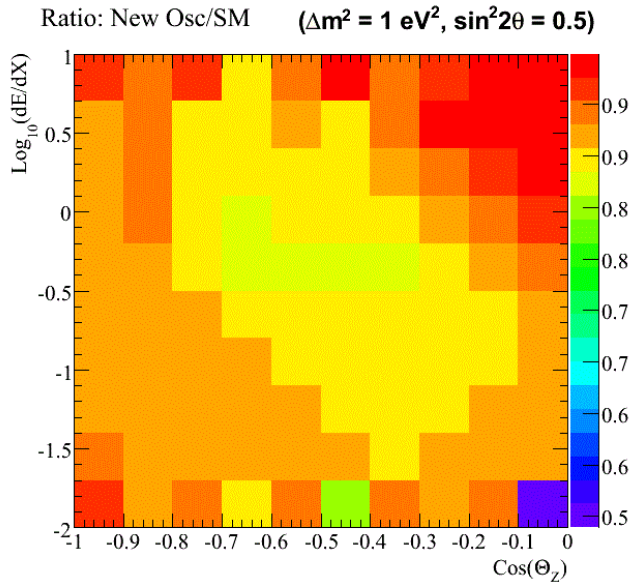$\bar{\nu}_\mu$ to sterile in Earth

ν_μ or $\bar{\nu}_\mu$ to sterile in vacuum

ν_μ to sterile in Earth

$\overline{\nu}_\mu \leftrightarrow \overline{\nu}_s$ **Signatures in 40-str IceCube**
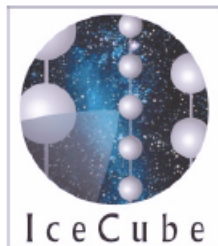
Methodology: Likelihood Analysis

Likelihood ratio with Feldman-Cousins ordering principle to determine exclusion regions

Binned in Energy Estimator (dE/dX) and $\cos(\theta_z)$

- 10 bins in dE/dX
- 10 bins in $\cos(\theta_z)$

$$R \sim \chi^2\left(\theta_r^{\text{current point}}, \theta_s^{\text{for BF at current pt}}\right) - \chi^2\left(\theta_r^{\text{BF point}}, \theta_s^{\text{BF point}}\right)$$

Test statistic:

$$R = -2\ln\frac{L_0}{\hat{L}}$$

L_0 = max likelihood with physics params fixed (nuisance params free)

$\hat{L}$ = max likelihood with all params free

Likelihood function:

$$L\left(\{n_{ij}\} \mid \{\mu_{ij}\left(\theta_r, \theta_s\right)\}\right) = \prod_{i,j}\frac{\mu_{ij}^{n_{ij}}}{n_{ij}!}e^{-\mu_{ij}}$$

θ_r : Physics Parameters

θ_s : Nuisance Parameters

Feldman-Cousins ordering:

(1) compute R's for ~1000 toy MC experiments at each point in physics parameter space

(2) R_{crit} = value of R such that $X\%$ of MC experiments (performed at that point in physics parameter space) have $R < R_{crit}$

(3) point is within allowed region if $R_{data} < R_{crit}$ at that point

Nuisance parameters handled using profile construction method
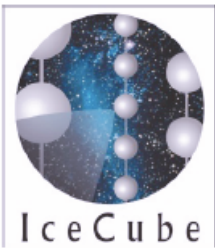
Flux Modeling

Event weights in predicted flux:

$$w = \varepsilon \left(\frac{E}{E_{ref}} \right)^{\Delta\gamma} \left[1 + 2\alpha \left(\cos\theta_z + \frac{1}{2} \right) \right] \left\{ \left[1 + 2\alpha_c \left(\cos\theta_z + \frac{1}{2} \right) \right] w_C + A_p \left(\frac{E}{E_{ref,p}} \right)^{\Delta\gamma_p} w_P \right\} P_{\nu_\mu \circledR \nu_\mu} (\theta_r)$$

w_C : "Honda_2006" conventional atmospheric neutrino spectrum

(Honda et al, PRD 75, 043006 (2007))

w_P : "Sarcevic_std" prompt atmospheric neutrino spectrum

(Enberg, et al, hep-ph 0806.0418)

(atmospheric neutrino spectra extended to energies above a TeV in NeutrinoFlux Class)

$E_{ref} \approx 1$ TeV

$E_{ref,p} \approx 5$ TeV

$P_{\nu_\mu \circledR \nu_\mu} (\theta_r)$: oscillation or decoherence survival probability;

θ_r = model dependent physics parameters

Nuisance Parameters (θ_s) : $\varepsilon, \Delta\gamma, \alpha, \alpha_c, A_p, \Delta\gamma_p$

Muons from taus:
➢ If muon neutrinos are oscillating to tau neutrinos, some of these tau neutrinos can produce muons in detector via tau's decay chain
➢Can account for in simulation chain

IC40 sensitivity for sterile neutrinos
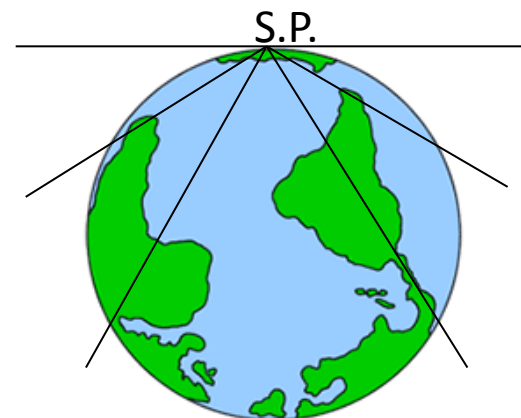

$\overline{\nu}_\mu$ mix with sterile at high Δm^2

PRELIMINARY SENSITIVITY ESTIMATE
40-string IceCube
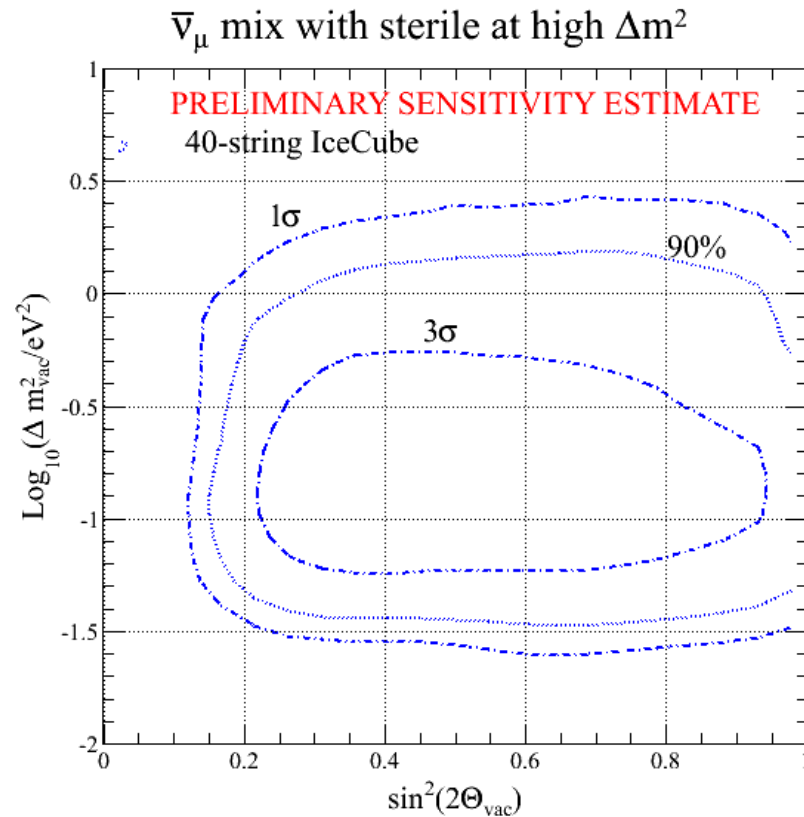
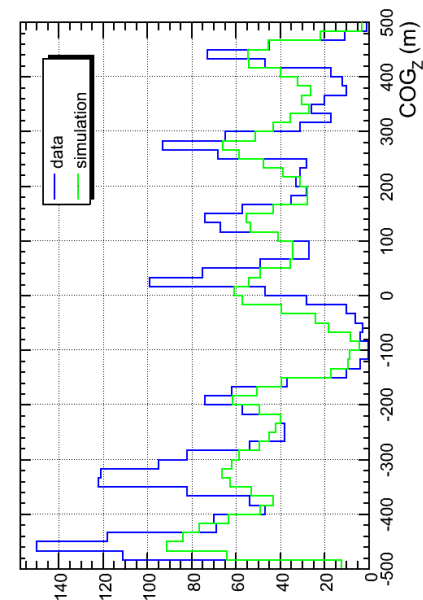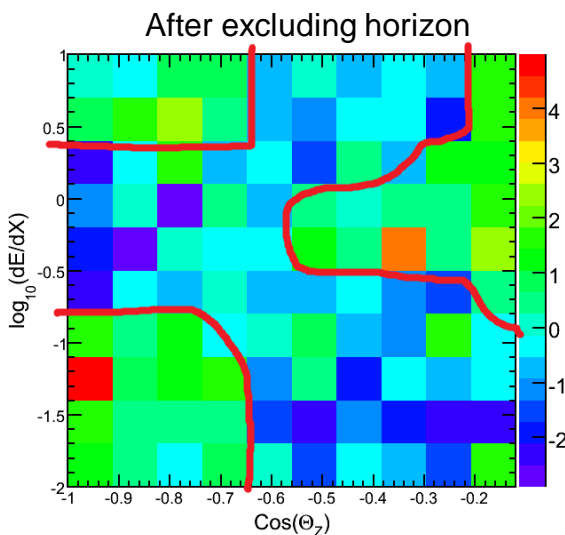plot assumes only $\overline{\nu}_\mu \leftrightarrow \overline{\nu}_s$

Based on likelihood analysis with nuisan ce parameters

Apparent "Excess" near horizon
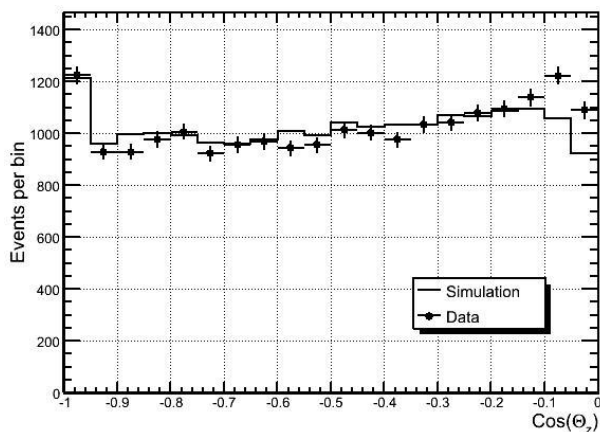
Bin-by-bin statistical significance of data/MC disagreement

$$(data - mc)/\sqrt{mc}$$
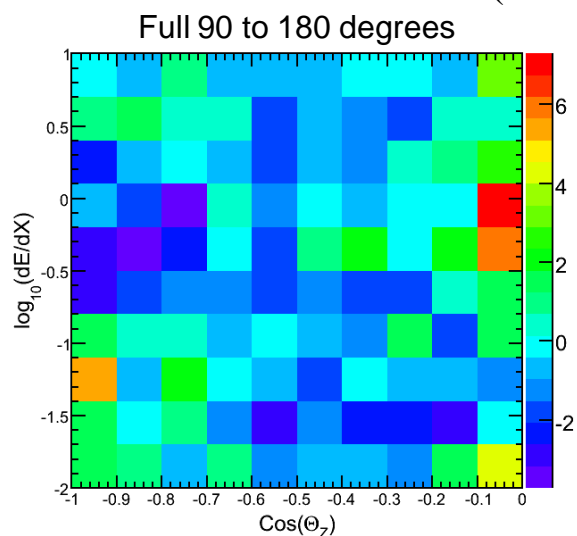
Full 90 to 180 degrees

After excluding horizon

Systematic Uncertainties

- Atmospheric variability?
- Ice Model/photon prop code?
- Cosmic ray muon background?
- Muon propagation code?
- DOM sensitivity and angular acceptance?
- Hole ice?
- New physics?
- Other?

Impact of systematic uncertainties in ice modeling:

Zenith distributions from MC (preliminary)

Ratio of effective areas from MC (preliminary)
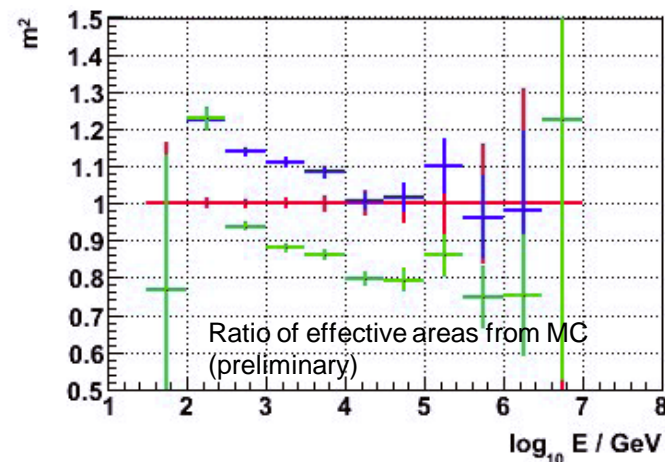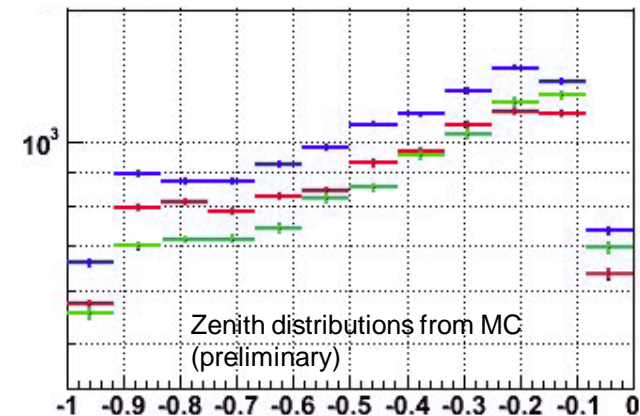
Alternate test statistic with error matrix of correlated errors

(Nuisance parameters do not adequately describe energy and zenith dependent uncertainties and correlations between bins)

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}\left(X_i - D_i\right)\left(M^{-1}\right)_{ij}\left(X_j - D_j\right) + \ln\left(\left|M\right|\right)$$

N = number of bins $\left(80 \text{ for } 8\text{x}10 \; dE \,/\, dX \text{ vs. } \cos(\text{zen})\right)$

M has 6400 elements

$$M_{ij,\alpha} = \left(X_i\left(\alpha\right) - X_i\left(CV\right)\right)\left(X_j\left(\alpha\right) - X_j\left(CV\right)\right)$$

α is a particular systematic variation, CV is central value

$$M_{ij} = \sum_{\alpha} M_{ij,\alpha} + \delta_{ij}x_i$$

$M_{ij,\alpha}$: OM sensitivity, ice model, photon propagation, cross sections, atmospheric variability, neutrino production model, muon propagation code, cosmic ray flux (composition and spectrum), reconstructions, angular acceptance, etc...

Alternate test statistic with error matrix of correlated errors

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}\left(X_i - D_i\right)\left(M^{-1}\right)_{ij}\left(X_j - D_j\right) + \ln\left(|M|\right)$$

Test Statistic:

$$\Delta\chi^2 = \chi^2\left(X(\theta), M(\theta)\right) - \chi^2\left(X(\theta_{bf}), M(\theta_{bf})\right)$$

where θ represents the physics parameters for the disappearance model being tested and bf is the best fit point

Can also include nuisance parameters with pull terms:

$$\frac{\left(\bar{\alpha} - \alpha(\theta)\right)^2}{\sigma_\alpha^2}, \quad \bar{\alpha} = \text{expected mean for param } \alpha$$
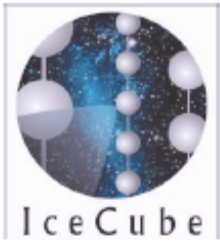
Summary

- IceCube is fully functional and searching for a variety of anticipated and unknown astrophysical signals
    - Anticipate new discoveries in next couple(few) years

- The characteristics of IceCube that will enable it to open up a neutrino window to the universe also make it ideal for studying high energy atmospheric neutrinos

- IceCube will be able to weigh in on the sterile neutrino debate, as well as other new physics models that alter the energy and zenith dependence of the flux of high energy atmospheric neutrinos

- Once we get the systematic uncertainties under control…

- Plan to perform the analysis on IC59 data